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A numerical study of baroclinic circulation in Monterey Bay

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

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THESIS

A NUMERICAL STUDY OF BAROCLINIC CIRCU-
LATION IN MONTEREY BAY

by

Barry L. Bruner

March 1988

Thesis Advisor   D.C. Smith IV

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The circulation of Monterey Bay is both variable and complex, and is likely to be significantly influenced by circulation in the adjacent California current. To study this circulation a two-layer, numerical model was used. The model was forced by inflow and outflow at an open boundary that connected the Pacific Ocean with the bay. Topography representing Monterey Canyon was included in the lower layer of the model. The effects of wind and tidal forcing were not considered. Results indicate that surface circulation is strongly constrained by topography when the lower layer flow is 5 cm/sec or larger and that the flows within the bay are consistent with geostrophic, vorticity-conserving flow over bottom topography. The sensitivity of the model to the distribution and strength of inflow and outflow forcing location was investigated. The model was found to be sensitive to the location of inflow and outflow forcing and also to the inflow and outflow vertical structure.

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A Numerical Study of Baroclinic Circulation in Monterey Bay

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The circulation of Monterey Bay is both variable and complex, and is likely to be significantly influenced by circulation in the adjacent California current. To study this circulation a two-layer, numerical model was used. The model was forced by inflow and outflow at an open boundary that connected the Pacific Ocean with the bay. Topography representing Monterey Canyon was included in the lower layer of the model. The effects of wind and tidal forcing were not considered. Results indicate that surface circulation is strongly constrained by topography when the lower layer flow is 5 cm/sec or larger and that the flows within the bay are consistent with geostrophic, vorticity-conserving flow over bottom topography. The sensitivity of the model to the distribution and strength of inflow and outflow forcing location was investigated. The model was found to be sensitive to the location of inflow and outflow forcing and also to the inflow and outflow vertical structure.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. THE MONTEREY BAY

Monterey Bay is located on the western coast of the United States approximately one hundred twenty miles south of San Francisco and two hundred fifty miles north of Los Angeles. The bay is nearly semi-elliptical in shape with a major axis of twenty two miles and a width of about eleven miles. The Monterey bay is depicted in Figure 1. The bay is divided into nearly equal halves by a submarine canyon which begins at Moss Landing and runs generally westward out of the bay into the Pacific Ocean. This submarine canyon is a major depression in topography whose features are as large as the Grand Canyon in vertical relief. At the mouth of the bay the canyon reaches a depth of over 5000 feet and slopes variably upward from there to Moss Landing, affording deep oceanic water access along the center of Monterey Bay. The effect of the Monterey submarine canyon on the flows within the bay are investigated in this study. There are few topographic features which are as vertically extensive as the Monterey submarine canyon, in an enclosed bay.

A seasonably variable offshore current flows outside of the bay along the western coast of the United States and California. From November to February this current is generally poleward and is commonly called the Davidson current. During the rest of the year the current flow reverses, flowing equatorward and is called the California Current (Hickey, 1979). The California current is frequently broken into upwelling and oceanic seasons. This study assumes that the offshore current flows are the driving force for the circulation within Monterey Bay.

Coastal upwelling occurs quite often in the area of Monterey Bay. A combination of a subtropical high pressure cell to the south and a continental thermal low over California is the driving force for the north-westerly winds which produce this upwelling (Hickey, 1979). The north-westerly winds produce an Ekman flow which has its maximum speed at the surface and decreases with depth. Due to conservation of mass considerations, there must be inflow from the left of the wind direction, to replace the flow departing to the right. Water comes up from below the surface to replace the water along the coast, thus causing upwelling (Pond and Pickard, 1983). The main period of upwelling generally begins in late February or early March and extends to late August or early September.
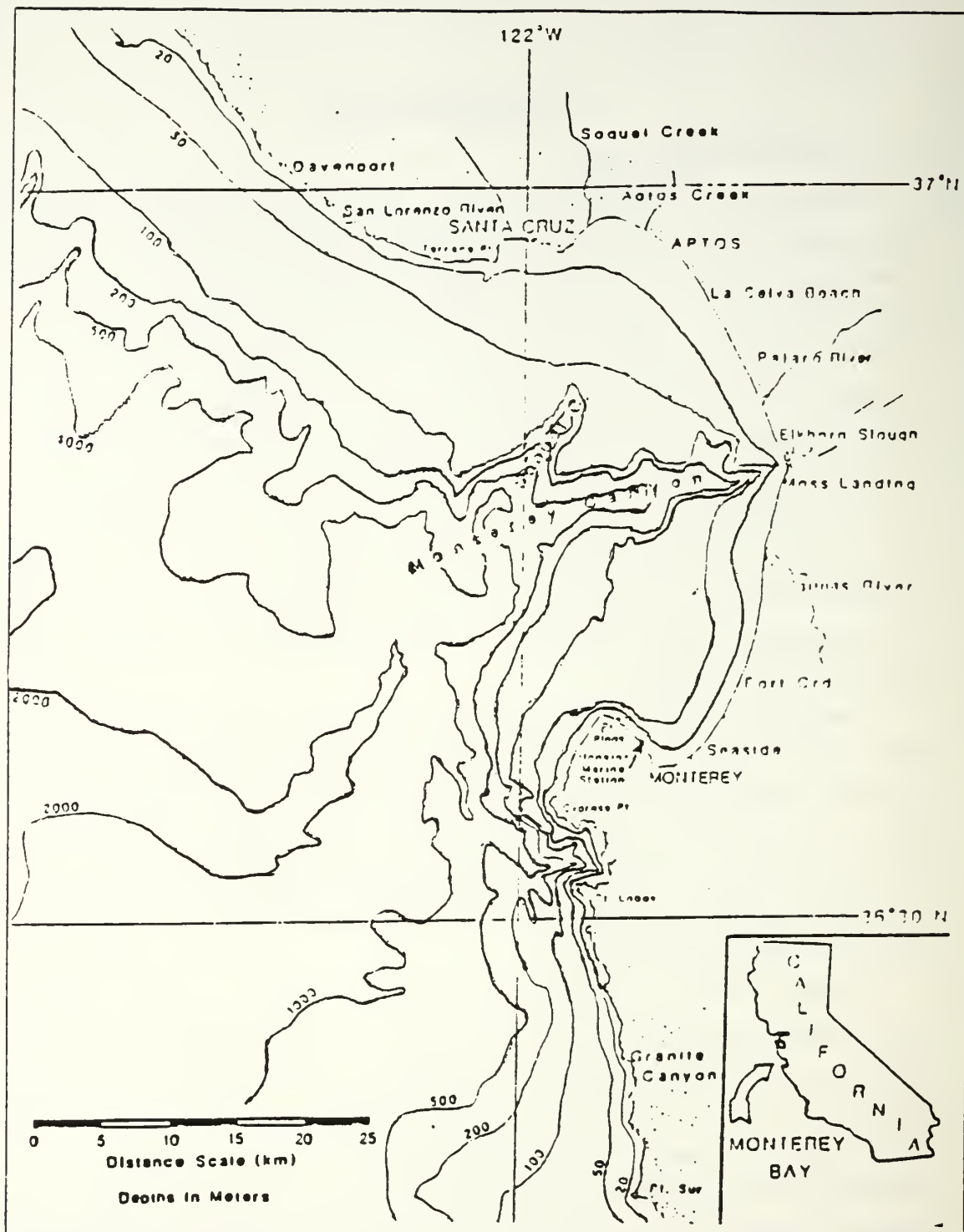
Figure 1.   Monterey Bay

2

A single layer model was previously used to study circulation in the Monterey Bay (Garcia, 1971). One of the purposes of this research was to compare the present two layer numerical model with this previous study and with historical observations of flow within Monterey Bay.

B. PREVIOUS STUDIES

Garcia (1971) reported the results of the first numerical study of the circulation within Monterey Bay. He attacked this problem in two phases. The first phase of the study consisted of a one layer numerical model of a simple cavity flow problem, whose boundaries were representative of Monterey Bay. The model was forced by poleward flow outside the bay. Upon solving the question of simple cavity flow, Garcia's work continued on to a second phase which looked at a refined model of Monterey Bay. In his refined model, Garcia included the effects of bottom topography, frictional forces and the Coriolis force. The topography used was a smoothed version of the topography found in Monterey Bay. The results of this model indicated that the presence of the submarine canyon was a probable cause for closed circulation within the boundaries of the bay and that the change of Coriolis force with latitude and the relative magnitude of the bottom friction forces could be assumed to be negligible.

Experiment results showed either cyclonic or anticyclonic flow, dependent on the inclusion of modeled bay topography and the Monterey Submarine Canyon. Figures 2a and 2b are examples of Garcia's results where hypothetical bottom topography without the submarine canyon was used (Figure 2a), and where the Monterey Submarine Canyon was included in the idealized topography (Figure 2b). In both of these experiments, Garcia included a constant Coriolis and frictional force. All of Garcia's modeled experiments were run with offshore flow in a poleward direction only. Equatorward flow was not considered.

Breaker and Broenkow (1988) summarized previous studies concerned with the flow within Monterey Bay. From temperature and salinity measurements made in 1928, to the use of satellite imagery in 1986, an examination of previous studies was presented. Although many sources of information are available for describing certain aspects of circulation in the bay, a complete picture of the general circulation is not clear from these previous studies. This is most probably due to the fact that the circulation within the bay is both spatially and temporally variable and weak in magnitude (Breaker and Broenkow, 1988).

Figure 3 depicts a vertical cross section of geostrophic velocities across the mouth of Monterey Bay. On 8 November 1987, in conjuction with Naval Postgraduate School class number OC-3570 (Operational Oceanography), the research vessel *Pt. Sur* made a single section track across the mouth of Monterey Bay from 36.92N, 122.12W, to 36.62N, 122.02W. Along this section nine CTD casts were collected. During each CTD cast, data was recorded from the surface to near the bottom in 25m increments. This data was later used to calculate geostrophic velocity, with the level of no motion being the shallowest bottom depth between each of two adjacent casts. The calculated geostrophic velocity results exhibit relatively rapid flow (25cm/sec) near the center of the canyon at approximately 150m depth. Above and below this depth the calculated geostrophic velocities are slower, ranging from 0 to 20cm/sec (Bruner, 1987).

According to Broenkow and Smethie (1978), the surface circulation in the bay, close to shore, is predominantly to the north, but reversals in flow direction can occur. These flow reversals may be either locally forced or related to coastal circulation further offshore. Breaker and Broenkow (1988) concluded that circulation in Monterey Bay is strongly influenced by offshore circulation.

The deep circulation in the bay is not as well documented as the surface circulation. The work of Lammers (1971), shows a warm cell centered over the Monterey Canyon in the 10 - 12 degree centigrade isotherms during much of the year (see Figure 4, taken from Breaker and Broenkow, 1988). This suggests anticyclonic circulation at intermediate depths. Even deeper in the canyon, Breaker and Broenkow (1988) state that the flow is frequently toward the head of the canyon. Figure 3 however shows substantial offshore flow inside the canyon. Breaker and Broenkow speculate that deep flow in the canyon may be influenced by the offshore Davidson and California currents.

Breaker and Broenkow (1988) have analysed the flow in terms of three layers. The surface, intermediate and deep flows are all contrasted by variation in magnitude and direction. It is quite possible that the layered flows may travel in opposite directions, e.g. cyclonic versus anticyclonic. Magnitudes for the surface flows have been estimated to range from 5 to 25 cm/sec. The flows at greater depths are not as easily defined, but are generally considered to be slower than the flow at the surface.

C. PURPOSE OF THIS STUDY

The purpose of this study is to determine how circulation in Monterey Bay responds to offshore circulation. A two layer numerical model is used. As upper and lower layer flows are not known, they will be varied among experiments to determine the sensitivity
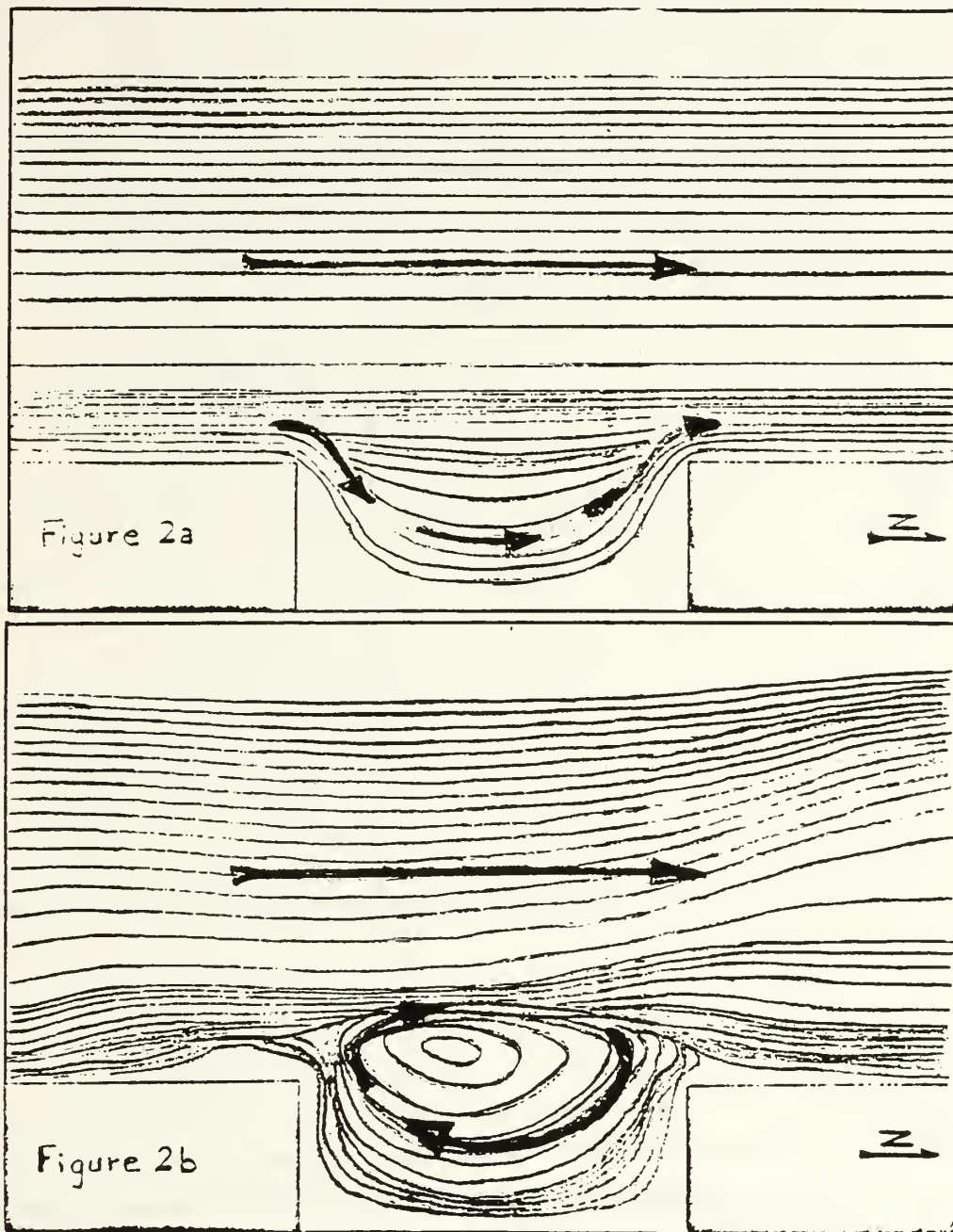
Figure 2. Results of Garcia's one layer model: Figure 2a depicts Garcia's results for an experiment in which the Monterey Submarine Canyon was not included, while Figure 2b is the result of an experiment in which the Monterey Submarine Canyon was included.
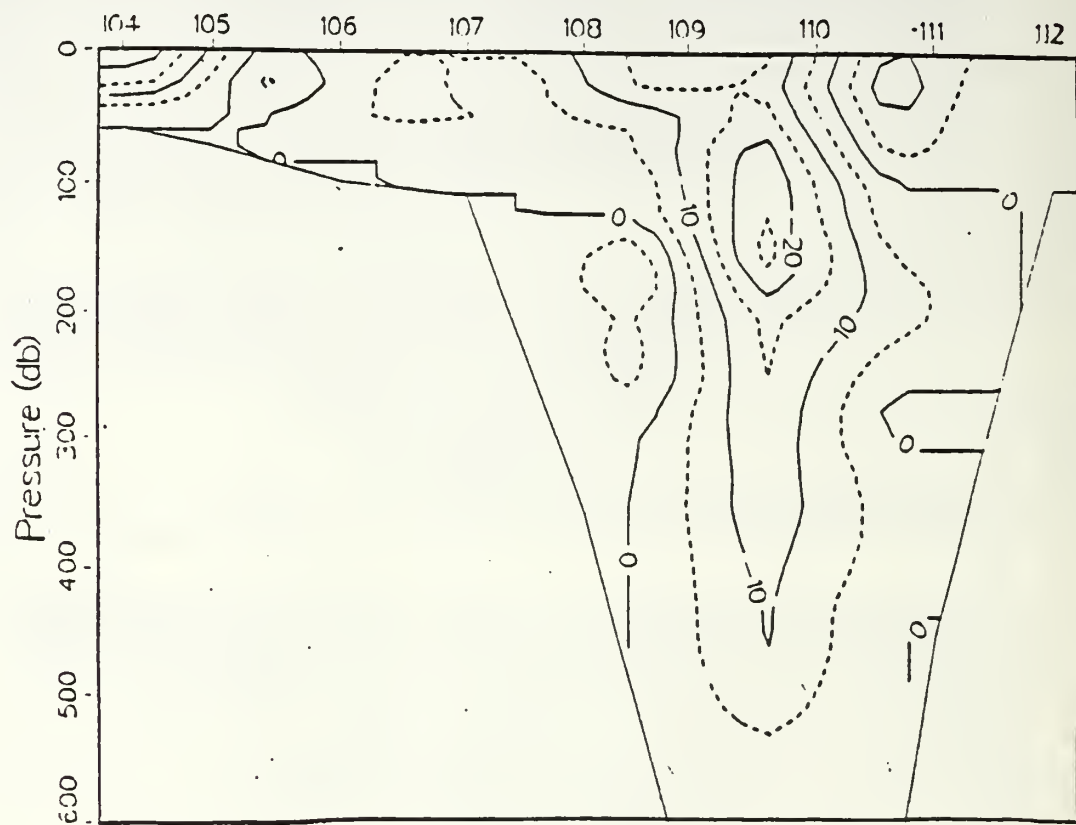
Figure 3.   Vertical cross section of geostrophic velocities: Figure 3 depicts a vertical cross section of geostrophic velocities across the mouth of Monterey Bay calculated from CTD data measured on 8 November 1987.   Level of no motion for geostrophic calculations was the shallowest depth between each two adjacent stations. Station 104 is located at 36.92N, 122.12W. Station 112 is located at 36.62N, 122.02W. Positive values as depicted on the figure indicate flow into the bay.

6
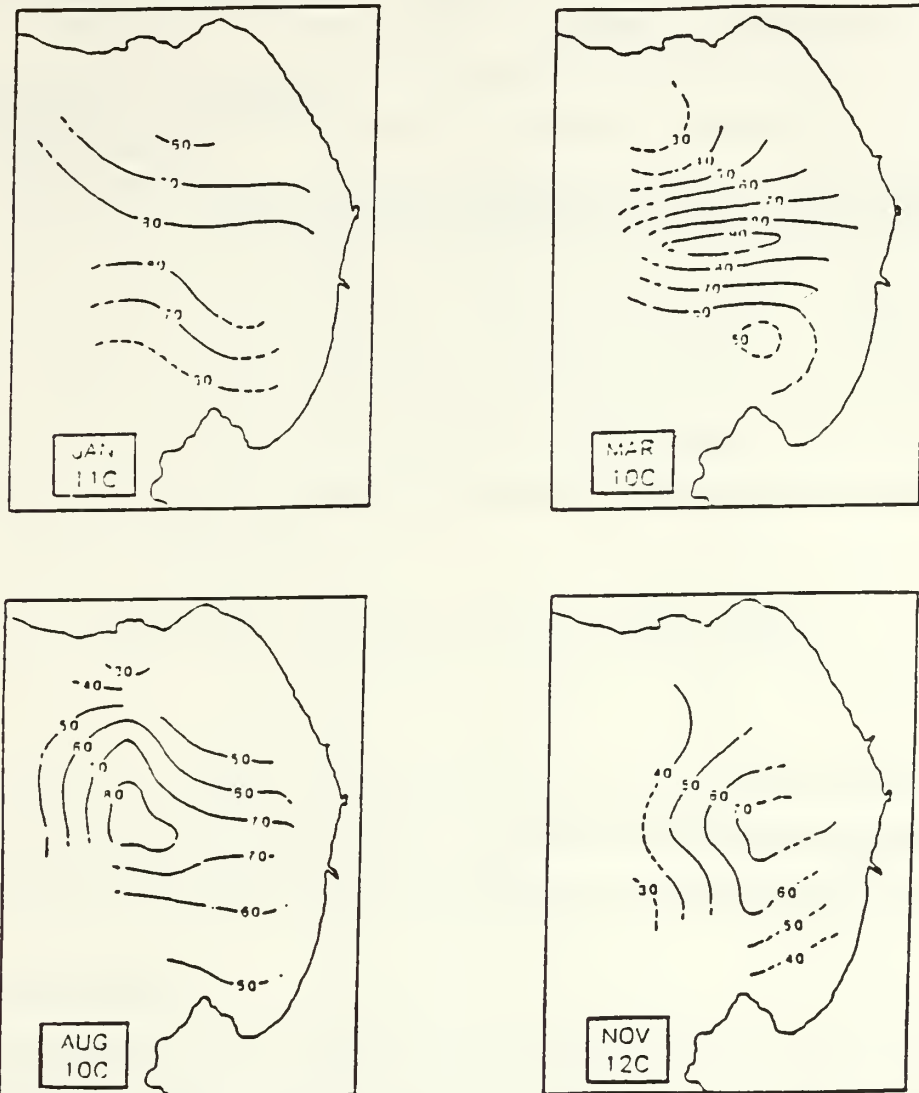
Figure 4. Lammers (1971). Warm cell centered over Monterey Canyon.: Monthly mean topographies(m) of selected isotherms for months where the thermal high located over Monterey Submarine Canyon is particularly well developed. (Adapted from Lammers, 1971.)

of the model to inflow and outflow location, magnitude and vertical shear. This study should not only model the bay circulation, but also provide guidance as to the forcing involved in creating those flows.

The details of the model formulation and the various model experiments performed during this research are discussed in Chapter two. The results of the various numerical experiments are discussed in Chapter three and in Chapter four, analysis of the experiments, conclusions and recommendations are presented.

II. NUMERICAL SIMULATION OF THE MONTEREY BAY

A. THE NUMERICAL MODEL

1. Model Equations

The circulation within Monterey Bay is modeled using a two layer, semi-implicit, primitive equation, numerical scheme. The basis for the numerical scheme contained within the model was initially developed by Hurlburt (1974) for use in ocean mesoscale circulation studies and has been employed numerous times (Hurlburt and Thompson (1980, 1982); Smith and O'Brien (1983)) quite successfully. Linear test cases have been run for comparison with linear analytic solutions (Smith and Reid, 1982) to show that this model is valid. Motion within each layer is governed by a momentum equation (2.1) and by a continuity equation (2.2).

$$\partial V_l/\partial t + (\nabla \cdot V_l + V_l \cdot \nabla)V_l + k \times fV_l = -h_l\nabla P_l + A_H\nabla^2 V_l \tag{2.1}$$

$$\partial h_l/\partial t + \nabla \cdot V_l = 0 \tag{2.2}$$

Variables and notation are defined in the appendix. The fluid in both layers is assumed to be hydrostatic and Boussinesq, and the fluid density in each immiscible layer is fixed. The effects of winds, tides, bottom friction and thermodynamics are not included.

2. Model Domain

A rectangular region (32.7km x 19.0km) contained within the bay was divided into 1.8 by 1.8 km squares to form the grid to be used for the numerical model finite differencing. By rotating the grid 17 degrees relative to lines of constant latitude and by centering the grid at 36.82N, 121.95W, the grid was oriented to be consistent with the boundaries of Monterey Bay.

Topography is included by applying a smoothed field of gridded bathymetry into the model for each corner of the 1.8km squares. Due to a model constraint that the layer interface cannot intersect the free surface or the topography, the shallowest topography was 100 meters. Because of this constraint, shallow topography and nearshore processes could not be included within this model. Figure 5 shows the topography used within the model, while Figure 1 shows the actual bay topography.
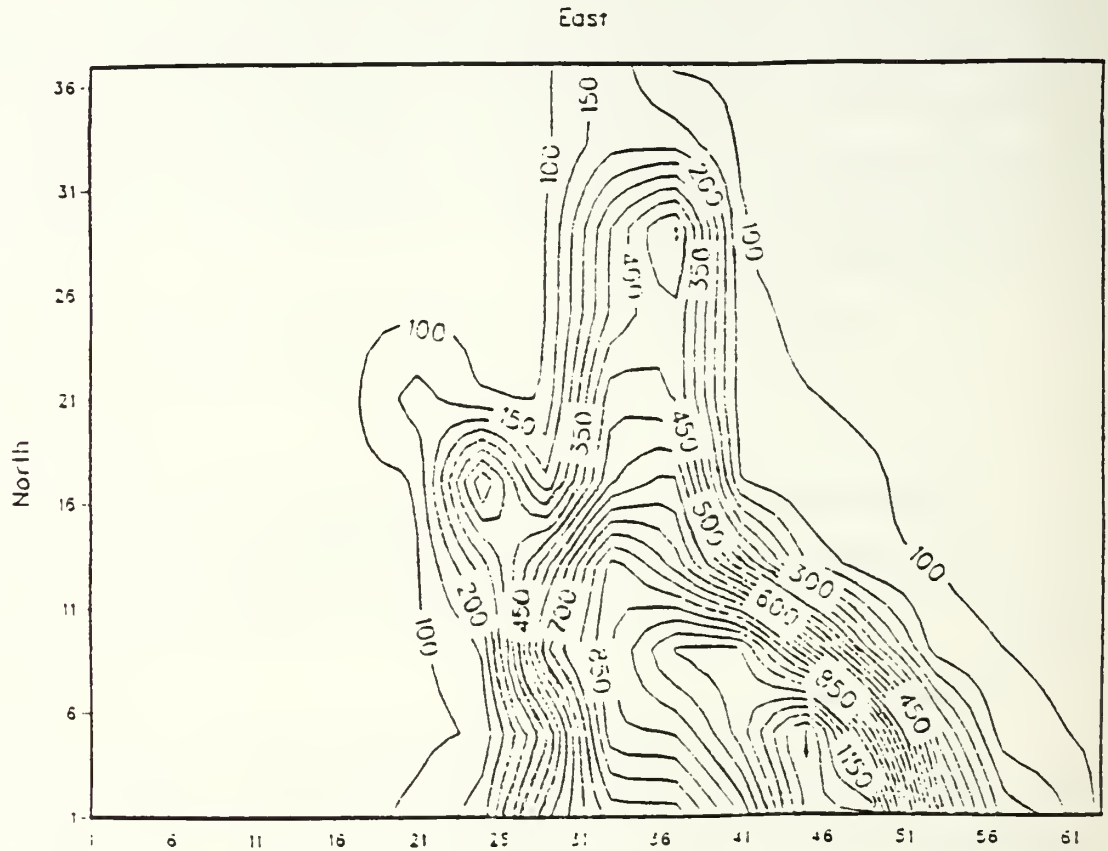
Monterey Bay Topography

Figure 5.   Modeled Monterey Bay Topography

3. Boundary Conditions

Two separate and distinct boundary conditions were used in this model. For the North, East and South sides of the bay a no-slip boundary condition was used. For the open (West side) portion of the bay a prescribed inflow and outflow boundary condition was set to represent offshore flow. The inflow and outflow specifications are described in greater detail in the following section. The inflow profile was uniform along the boundary with no horizontal shear. These basic boundary conditions were applied to both the upper and lower layers, the only difference being the strength and direction of flow prescribed in each layer. Various cases were run in which the shear between the upper and lower layers (and thus the prescribed boundary conditions) was altered. These will be described in the next section.

B. NUMERICAL EXPERIMENTS

1. The Reference State

In order to assess possible model outputs resulting from various parameter changes within a model, it is important that a reference state be established. The model reference state was selected because of its close resemblance in surface circulation to that inferred by remotely sensed imagery.

Two reference states were established for this study. Both were developed from remotely sensed imagery (NASA U-2 and LANDSAT) taken from October 1971 to June 1976. The imagery patterns were used for feature tracking of sediment flow within Monterey Bay, and seasonal circulation patterns were developed from these images by Pirie and Stellar (1977). The results, three current charts (Figures 6, 7, and 8) are shown. The first current pattern describes the surface currents during the upwelling season and is very similar to the third pattern, the surface currents during the oceanic season. The second current pattern represents the bay's general Davidson Current season's surface currents. These results suggest that when the flow outside the bay is a generally southward flowing California current, the circulation within the bay is a two cell system with anticyclonic flow in the mouth of the bay, and a cyclonic flow located in the inner portion of the bay. When the offshore flow is the poleward-flowing Davidson current, the flow field in the bay is generally a single cyclonic cell. Although these maps show some smaller circulation cells, results here are compared in terms of the larger circulation cells. It is important to note from these figures that the circulation along the inshore portion of the bay is largely to the north and independent of offshore flow direction.

11

Because of model geometry, alongshore flow cannot be used as a boundary condition to force the model. Instead, zonal flow is specified across the mouth of the bay. Although the results of Pirie and Stellar (1977) suggest inflow into the northern side of the bay during the California Current regime, and inflow into the southern side of the bay during the Davidson Current regime, the model is formulated in terms of zonal forcing at the mouth of the bay. Specifically, experiments forced at the north end of the bay will be contrasted with experiments forced at the south end of the bay.

Using these two current patterns as a guide, two different reference experiments were established, each best representing a generally southern, two gyre (Figure 9), or northern, single gyre (Figure 10) type flow within the bay.

A comparison of these two reference states illustrates an important difference in flow control in the lower layer. In the reference state forced at the north end of the bay, the lower layer is constrained largely due to the shallow flat portions of the bay and hence flows around the canyon. In the reference state forced at the south end, flow enters the bay over sloping topography. A comparison of Figure 9 and the topography (Figure 5), shows that the lower flow follows the bottom contours and is thus constrained to flow inside the canyon as opposed to the flow of the other reference state (Figure 10).

The initial inflows were set at 10 cm/sec and 1 cm/sec for the upper and lower layers respectively. These values were based predominantly on information discussed in the previous chapter. Both reference sets consist of two-layer flows in which the lateral profiles for inflow are Gaussian in distribution, and are of the form in equation (2.3).

$$V_i(I,J) = U_i(\exp(- X^2))/2(L)^2 \qquad i = 1,2 \qquad (2.3)$$

where L is the e-folding width scale of the flow, U_i is the amplitude coefficient, and X^2 is the lateral distribution of the flow along the boundary. The outflow is specified by a radiation boundary condition (Camerlengo and O'Brien, 1980).

2. Variation of Parameters

Each numerical simulation was run with the variation of one or more specific parameters from those of the reference state. Of specific interest was the effect of topography, flow distribution across the mouth of the bay, and of variations in vertical shear between the upper and lower layers. All numerical simulations were run for a minimum of 11 days, with some cases running up to 15 days, which is adequate in length for a well developed circulation pattern to evolve. In this section the results of the

Figure 6. Pattern of flow in Monterey Bay during the upwelling current season (February to August) taken from Pirie and Stellar, 1977.
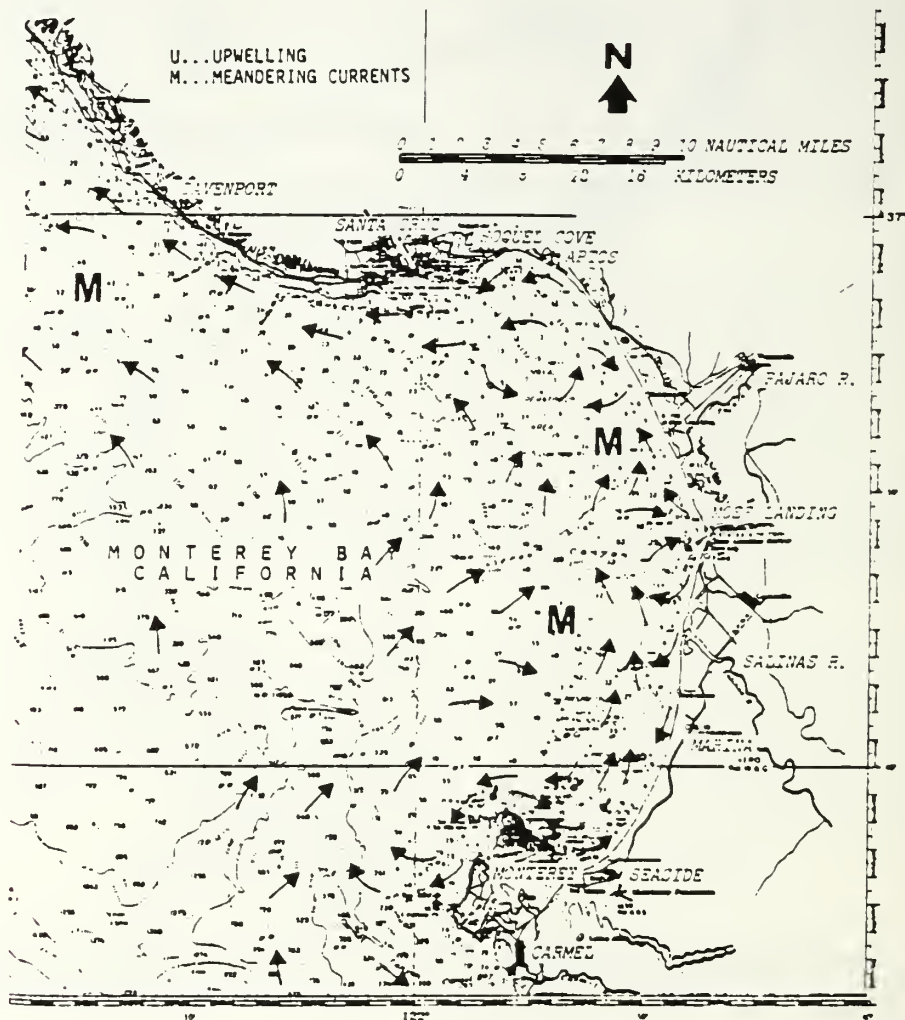
Figure 7.   Pattern of flow in Monterey Bay during the Davidson current season
(Nov. to Feb.) taken from Pirie and Stellar, 1977.
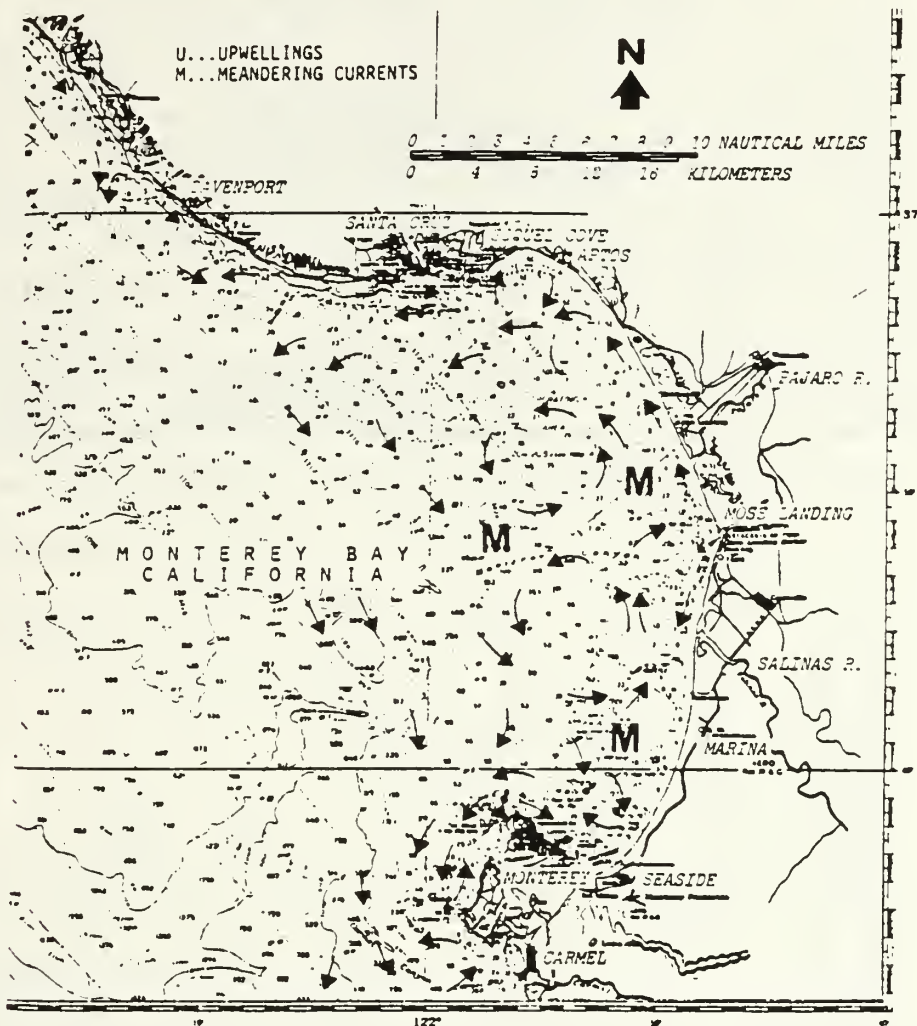
Figure 8.   Pattern of flow in Monterey Bay during the Oceanic current season
(September to October) taken from Pirie and Stellar, 1977.
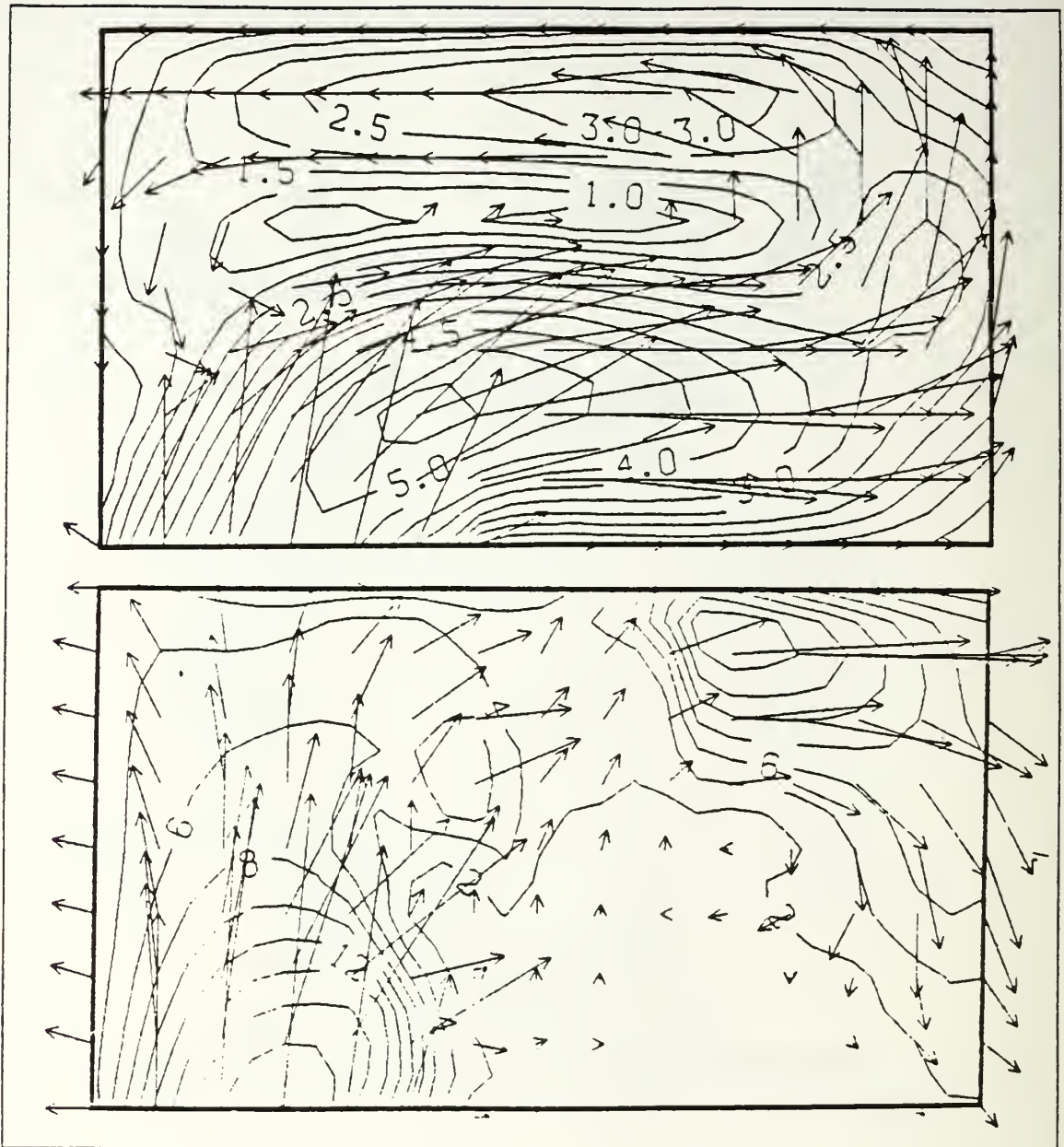
Figure 9. Reference state forced at the north side of the bay: The upper and lower figures respectively represent the upper and lower layer velocity fields for the reference state forced at the northern side of the offshore section. Isotachs are drawn at 0.5 cm/sec and 2 mm/sec intervals for the upper and lower figures respectively. North is to the left in each figure, and each figure represents a 32.7 by 19.0 km domain.
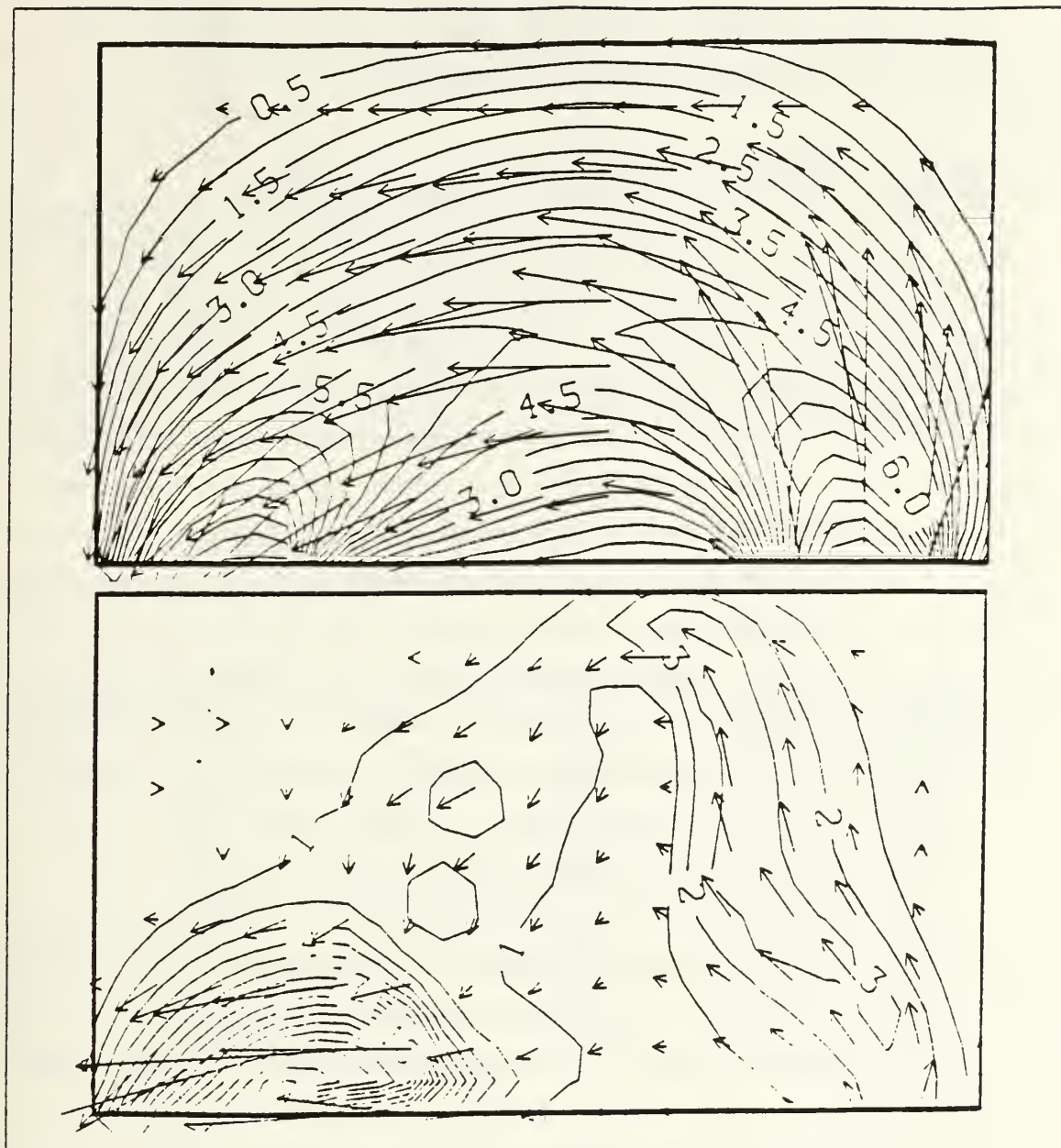
Figure 10.   Reference state forced at the south side of the bay: The upper and lower figures respectively represent the upper and lower layer velocity fields for the reference state forced at the southern side of the offshore section. Isotachs are drawn at 0.5 cm/sec and 1 mm/sec intervals for the upper and lower figures respectively.   North is to the left in each figure and each figure represents a 32.7 by 19.0 km domain.

17

experiments are described. The analysis of each result is in Chapter IV. Table 2 provides a list of those parameters varied in each experiment.

Table 1. REFERENCE STATE MODEL PARAMETERS

| Parameter	Symbol	North inflow ref. value	South inflow ref. value
Upper layer flow	U1in	0.1 m./sec.	0.1 m./sec.
Lower layer flow	U2in	0.01 m./sec.	0.01 m./sec.
Inflow location	Iin1 to Iin2	5-25 on grid	47-55 on grid
Outflow location	Iout1 to Iout2	26-55 on grid	5-15 on grid

a. Experiment No. 1 (N. inflow, flat bottom, 10/1 shear)

Bottom topography was removed completely to determine the model sensitivity to the simulated Monterey Bay topography. In this case the bottom is flat with a depth of 750 meters. Figure 11 shows the model output fields for upper and lower layer velocities. From these fields, it is apparent that the Monterey Canyon greatly influences the lower layer flow. While the upper layer appears relatively unchanged, the lower layer no longer follows the topography but instead follows the boundaries.

b. Experiment No. 2 (S. inflow, flat bottom, 10/1 shear)

Bottom topography was again removed, this time for the south forced current flow. Figure 12 shows the model output fields for the upper and lower layer velocities. The results are similar to those obtained during Experiment No.1. The upper layer velocity field appears relatively unchanged, following a cyclonic path around the boundaries, while the lower layer velocity field no longer follows topography, this time flowing with less of a cyclonic motion.

c. Experiment No. 3 (N. inflow, flat bottom, 10/5 shear)

Bottom topography was removed and lower layer flow was increased to 5 cm/sec. This decreased the shear between the upper and lower layers, allowing the lower layer flow to extend further into the model domain. The upper and lower layer velocity fields for this run are depicted in Figure 13. The increase in lower layer flow speed had a strong effect on the upper layer flow field. The anticyclonic portion of the upper layer two gyre system remains relatively unchanged while the cyclonic cell is much weaker.

18

d. Experiment No. 4 (N. inflow, topography, 5/1 shear)

Upper layer flow was reduced to 5cm/sec while lower layer flow remained the same as the reference state. The upper and lower layer velocity fields are depicted in Figure 14. The lower layer velocity field changed little from that of the reference state for the California current regime. The upper layer velocity field appears quite similar to that of the reference state with the exception that the flow magnitudes are 50% less.

e. Experiment No. 5 (N. inflow, topography, 5/5 shear)

Both upper and lower layer flows were forced at a magnitude of 5cm/sec, resulting in barotropic flow. Both upper and lower layer velocity fields were radically effected by this type of forcing. They are depicted in Figure 15. Lower layer flow follows an anticyclonic path around the canyon as in the reference state. Upper layer flow follows the lower layer flow to a large extent, without the cyclonic flow in the eastern part of the bay seen in the reference case.

Table 2.   VARIATION OF MODEL PARAMETERS

Experiment No.	U1in (m./sec.)	U2in (m./sec.)	Inflow location	Outflow location	Topography (y/n)
1	0.1	0.01	5-25	26-55	n
2	0.1	0.01	47-55	5-15	n
3	0.1	0.05	5-25	26-55	n
4	0.05	0.01	5-25	26-55	y
5	0.05	0.05	5-25	26-55	y
6	0.1	0.01	5-20	21-55	y
7	0.05	0.02	47-55	5-15	y

f. Experiment No. 6 (N. inflow, topography, 10/1 shear)

Upper and lower layer velocity magnitudes were unchanged from the reference state. The inflow width was changed to include locations 5-20, while the outflow width was increased to 21-55, as compared to the reference state. (Refer to Figure 5 for grid locations) The upper and lower layer velocity fields for this run are depicted in Figure 16. The upper layer flow is very different from that of the reference state in that the large cyclonic flow pattern of the reference state is no longer apparent. The lower layer is also quite different, exiting at a point much nearer its entrance into the bay.

g. *Experiment No. 7 (S. inflow, topography, 5/2 shear)*

Lower layer flow was increased to 2 cm/sec as compared with the south forced reference state, while upper layer flow was decreased to 5 cm/sec in an attempt to decrease the shear between layers. The inflow and outflow forcing locations remained the same. Figure 17 shows the upper and lower layer velocity fields for this experiment. A comparison of these output fields with those of the reference state do not show a significant difference.

3. The difference in forcing the bay from the north versus the south

Experiments have shown that the results obtained from forcing inflow into the southern end of the bay are not simply mirror images of those obtained when inflow is forced at the northen end of the bay. This is because the canyon, which strongly influences the results, is not symmetric in the center of the bay. Flow from the south has to enter over the sloping canyon, but flow from the north can enter over a shallow flat region. Flows from the south have to follow contours of the canyon bathymetry, whereas flows from the north can circumvent the canyon in response to flat bottom vorticity conservation.

Figure 11.   Experiment No.1 (N. inflow, flat bottom, and 10/1 shear): The upper
              and lower figures respectively represent the upper and lower layer ve-
              locity fields for Experiment No. 1. Isotachs are drawn at 0.5 and 0.05
              cm/sec for the upper and lower figures respectively. North is to the left
              in each figure and each figure represents a 32.7 by 19.0 km domain.
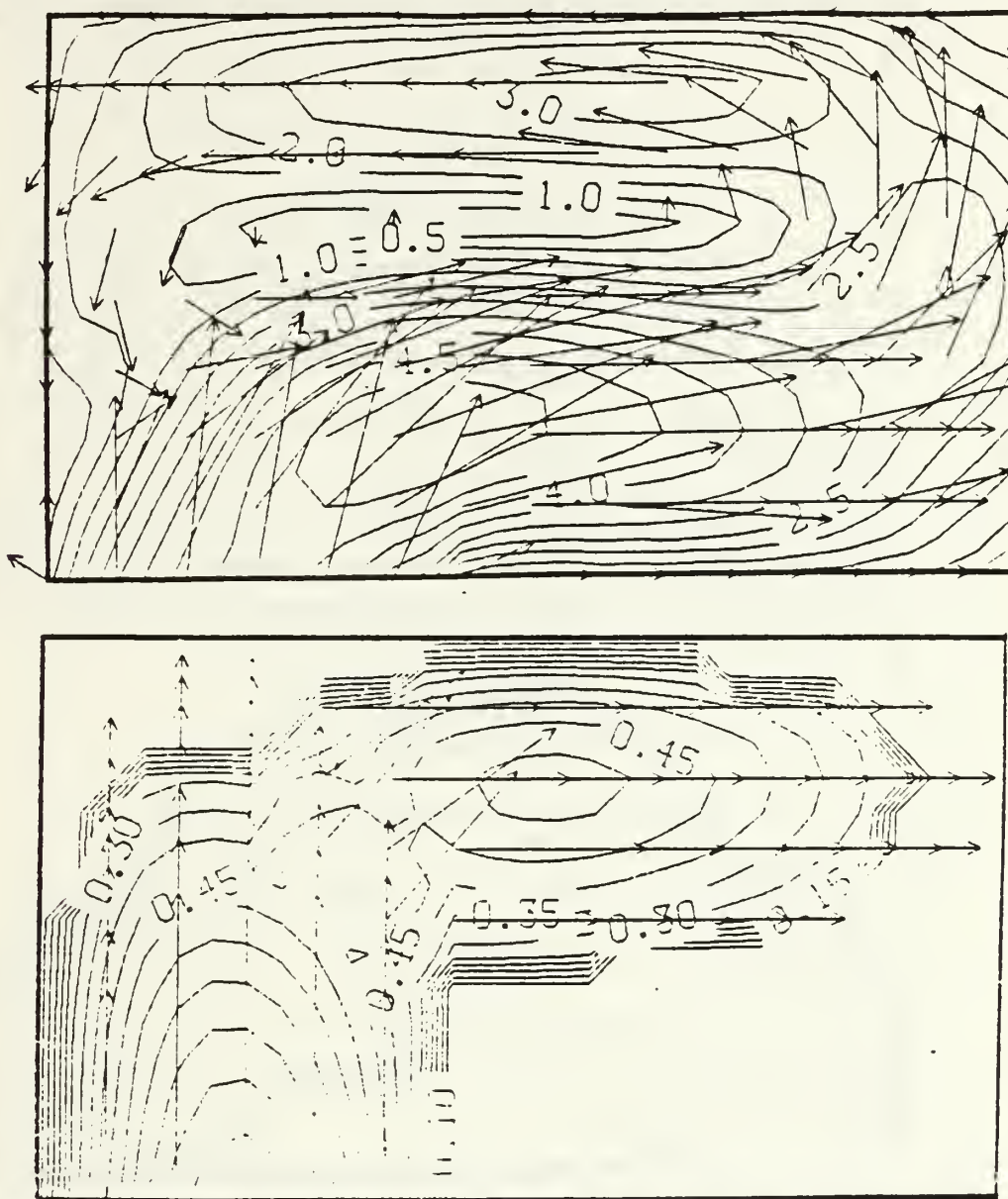
Figure 12. Experiment No.2 (S. inflow, flat bottom, and 10/1 shear): The upper and lower figures respectively represent the upper and lower layer velocity fields for Experiment No. 2. Isotachs are drawn at 1 and 0.05 cm/sec intervals. North is to the left in each figure and each figure represents a 32.7 by 19.0 km domain.

Figure 13.   Experiment No.3 (N. inflow, topography, and 10/5 shear):   The upper and lower figures respectively represent the upper and lower layer velocity fields for Experiment No. 2. Isotachs are drawn at 0.5 and 0.25 cm/sec intervals for the upper and lower figures respectively. North is to the left in each figure and each figure represents a 32.7 by 19.0 km domain.

Figure 14.   Experiment No.4 (N. inflow, topography, and 5/1 shear):   The upper
and lower figures respectively represent the upper and lower layer ve-
locity fields for Experiment No. 3. Isotachs are drawn at 0.25 cm/sec
and 1 mm/sec for the upper and lower figures respectively. North is to
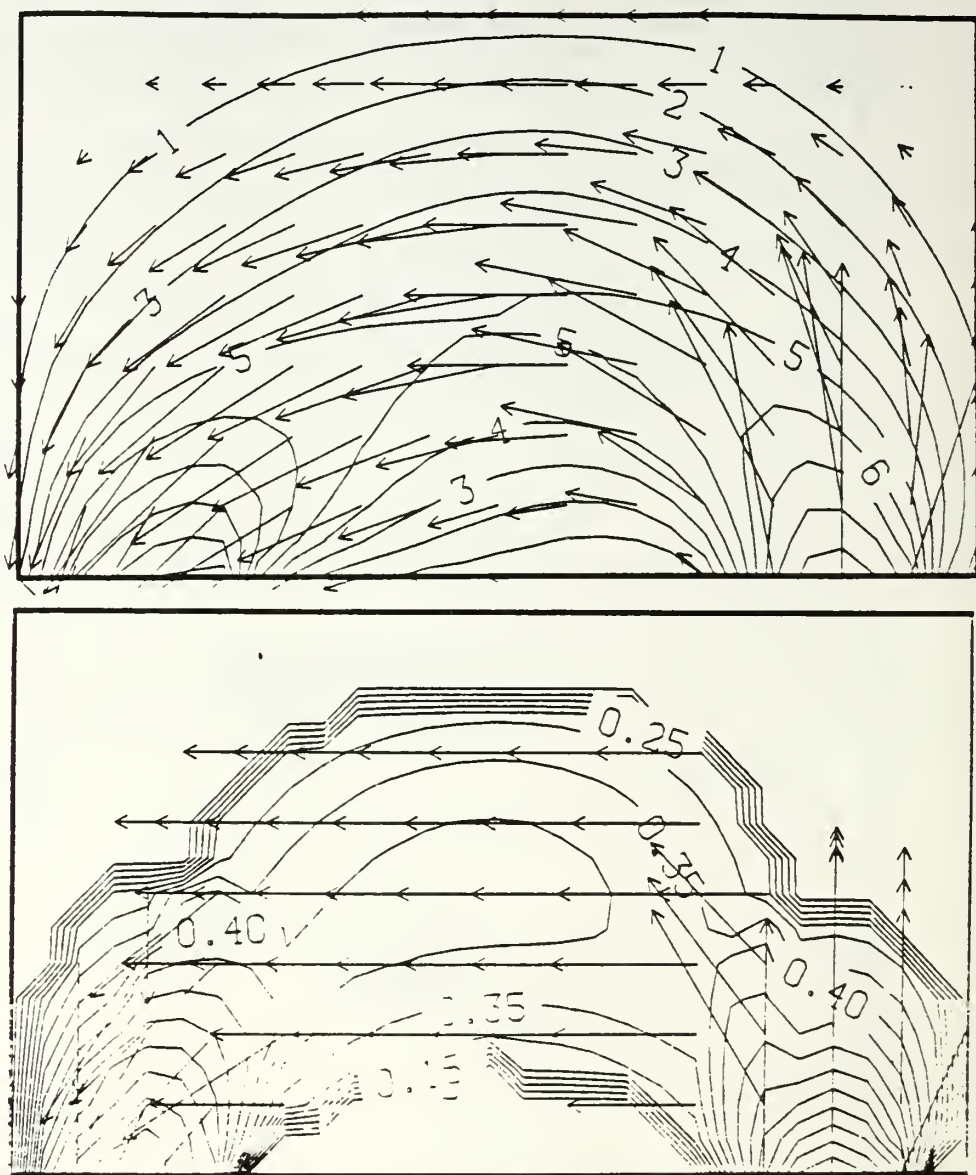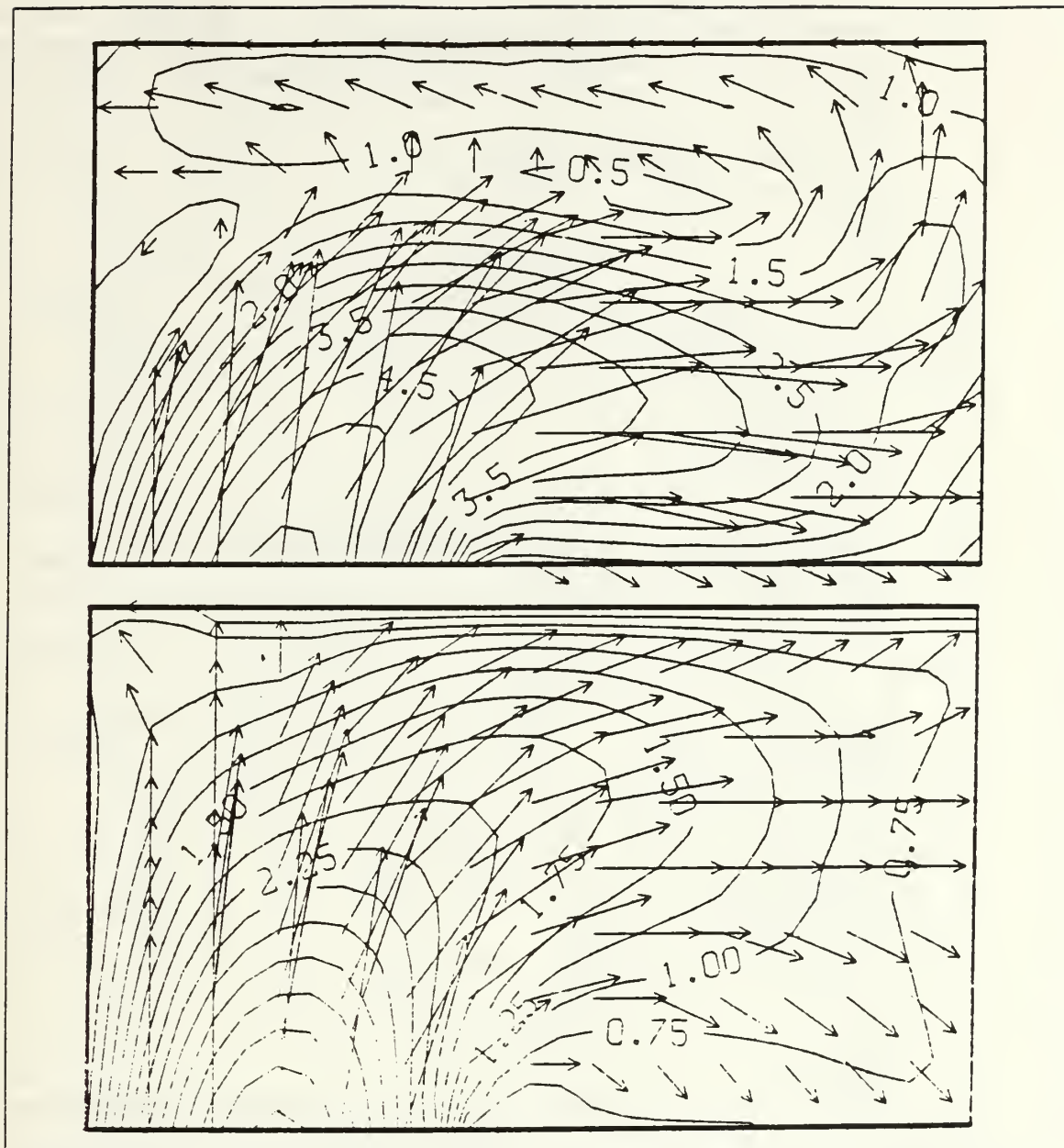the left in each figure and each figure represents a 32.7 by 19.0 km do-
main.

Figure 15.   Experiment No.5 (N. inflow, topography, and 5/5 shear):   The upper and lower figures respectively represent the upper and lower layer velocity fields for Experiment No. 5. Isotachs are drawn at 0.25 cm/sec and 5 mm/sec for the upper and lower figures respectively. North is to the left in each figure and each figure represents a 32.7 by 19.0 km domain.
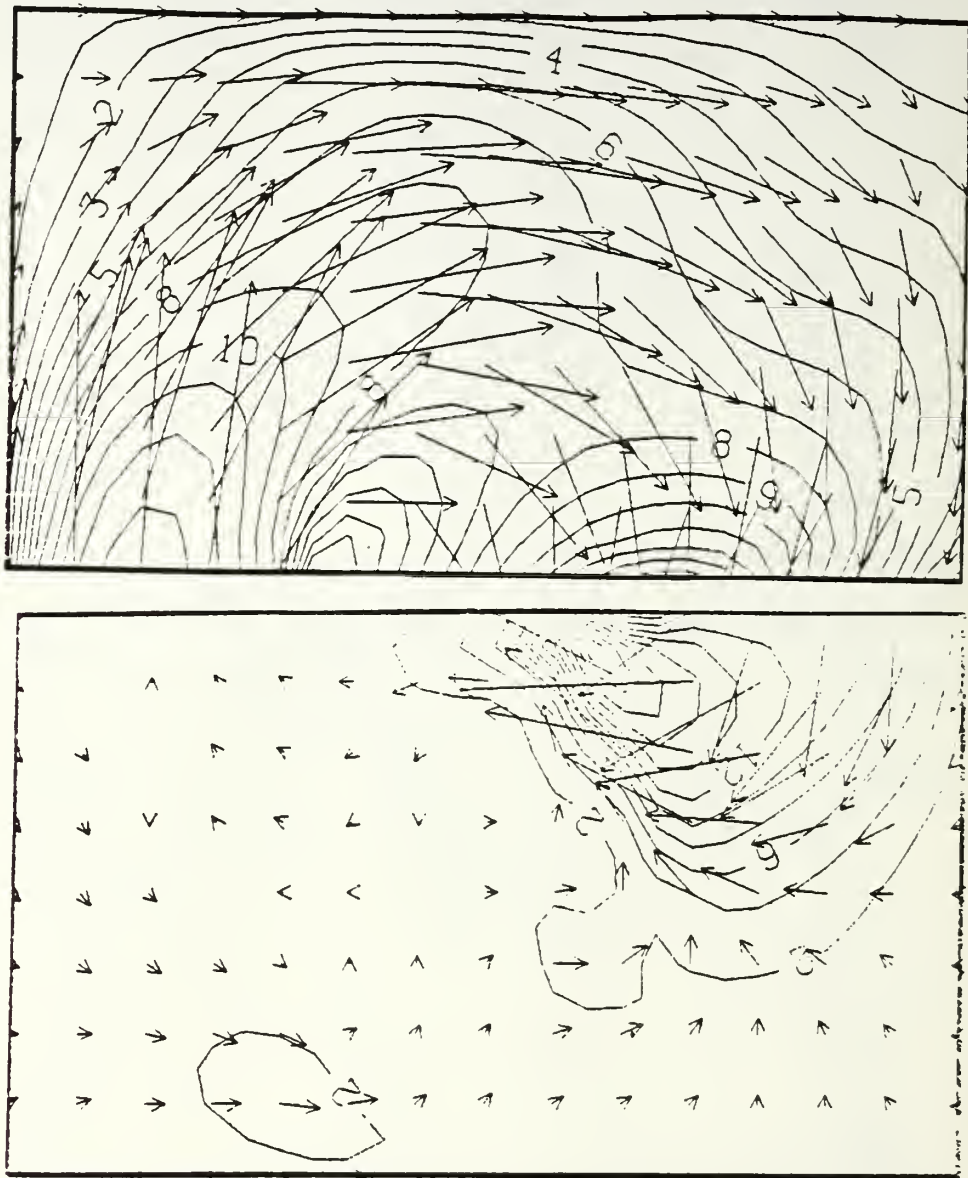
Figure 16.   Experiment   No.6   (N.   inflow,   topography   and   different
in/outflows):   The upper and lower figures respectively represent the
upper and lower layer velocity fields for Experiment No. 6.   Isotachs
are drawn at 1 cm/sec and 2 mm/sec intervals for the upper and lower
figures respectively. North is to the left in each figure and each figure
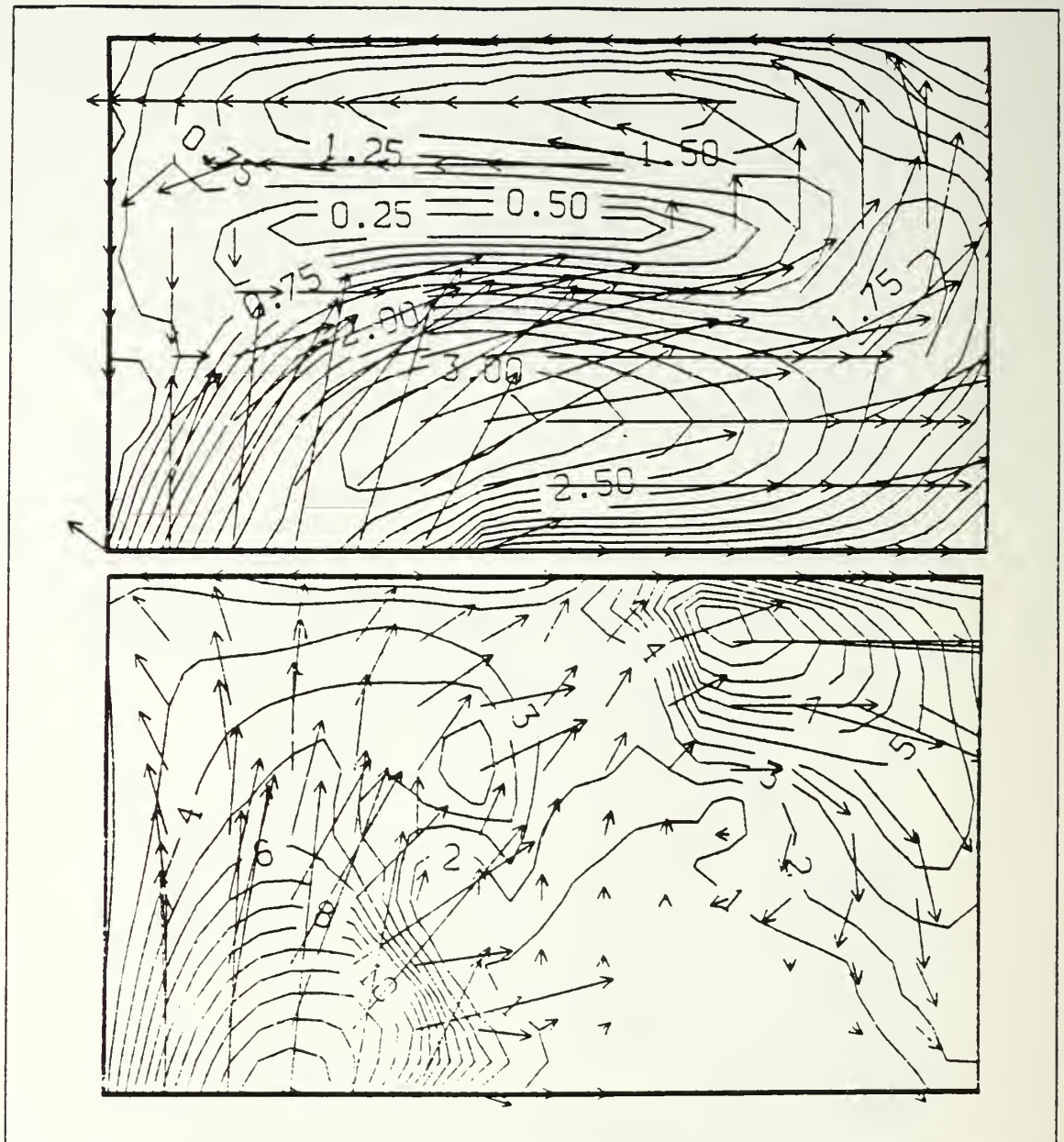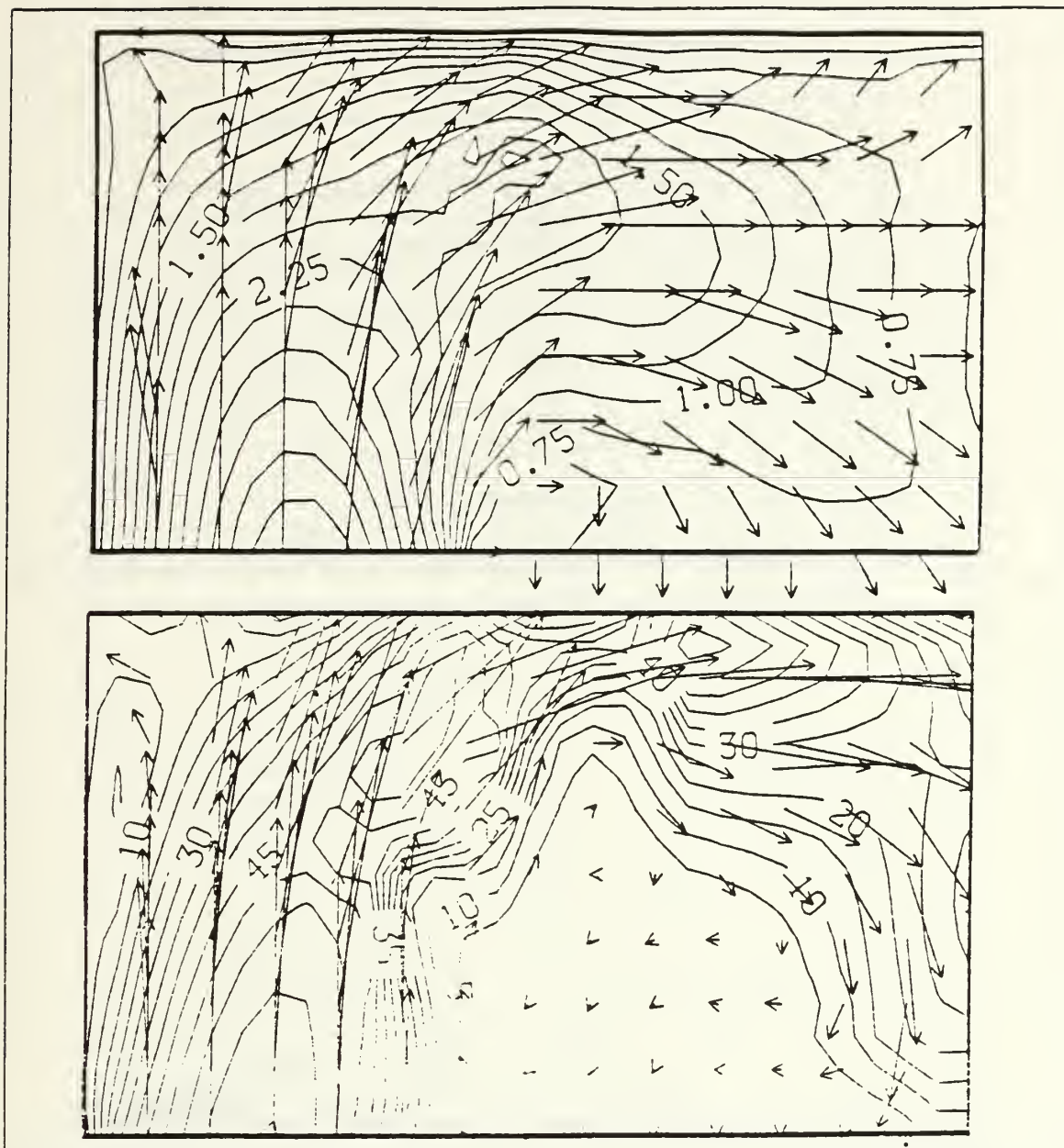represents a 32.7 by 19.0 km domain.

Figure 17.   Experiment No.7 (S. inflow, topography, and 5/2 shear):   The upper and lower figures respectively represent the upper and lower layer velocity fields for Experiment No. 7. Isotachs are drawn at 0.25 cm/sec and 2.5 mm/sec intervals for the upper and lower figures respectively. North is to the left in each figure and each figure represents a 32.7 by 19.0 km domain.
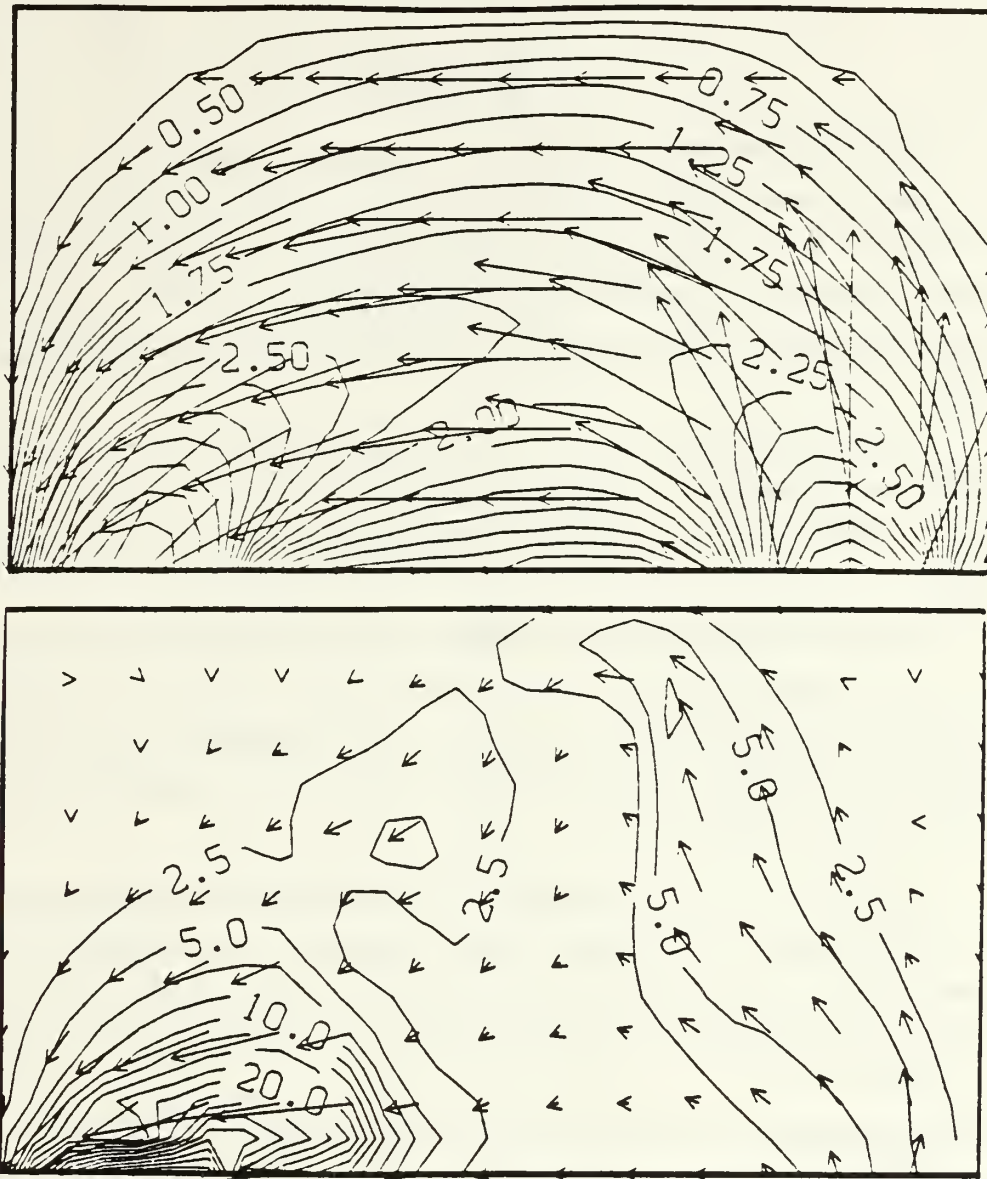
III. RESULTS

A. SENSITIVITY OF THE MODEL TO TOPOGRAPHY

Several calculations were made without the idealized topography of the bay. Experiments 1,2 and 3 were all conducted with simulated flat topography. Experiments 1 and 2 were conducted as variations on the main reference states for both north forced and south forced flow, while Experiment 3 added the complication of increased lower layer flow.

In both Experiment 1 and 2, the lower layer velocity field is greatly affected by the lack of topography. The flow magnitude in the lower layer is small enough however, so that the upper layer flow exhibits no discernible change due to the removal of topography.

Experiment 3 was run from a variation of the north forced reference state, the major difference being the increase in lower layer flow to 5 cm/sec. The lower layer flow is much more pronounced, beginning to resemble the reference upper layer flow. This increase in lower layer flow magnitude appears to also affect the upper layer, which though still resembling the reference state, begins to duplicate the lower layer.

B. SENSITIVITY OF THE MODEL TO LOCATION OF BOUNDARY FORCING

In Experiment 6 the inflow boundary condition was decreased in width to grid points 5-20, while the outflow boundary condition was increased to 21-55. This change, though small in comparison with the relative size of the reference boundaries, resulted in a significant change in the upper and lower layer velocity fields. The cyclonic circulation in the inner bay, so prevalent in the reference state upper layer flow (though relatively weak in magnitude at about 3 cm/sec), completely disappears. In this case the flow simply enters the bay from the north, flows anticyclonically along the boundaries of the bay, then exits to the south. The lower layer velocity field also shows a marked change from the reference state. The dominant lower layer flow appears to turn immediately upon entering the bay from the north, exiting rapidly to the south (See Figure 16).

C. SENSITIVITY OF THE MODEL TO VERTICAL SHEAR

The model was run with various shear flows between the upper and lower layers. The reference states were run with a large shear of 9 cm/sec between the two layers. The

most prevalent effect of a change in shear flow occurred between Experiments 4 and 5. In these two cases (one barotropic and the other baroclinic with a shear flow of 4 cm sec between layers), the results showed that either the magnitude of the lower layer flow or the shear between layers has the greatest effect upon the upper layer. For a slow lower layer flow (1 cm/sec), the lower layer does not appear to have any great effect upon the upper layer. Experiment 1 demonstrates this in that though the lower layer is very different from the upper layer, the upper layer velocity field does not change. For barotropic flow, however, the lower layer greatly influences the upper layer. This influence is demonstrated remarkably well in the results of Experiment 5 by a complete change in the upper layer flow from both the reference state and that upper layer velocity field gained in Experiment 4.

In the experiments run in this study (Experiments 3 and 5), the lower layer flow was increased to determine its effect on the upper layer. By increasing the lower layer flow, the shear between the upper and lower layers decreased. Due to model constraints, the upper layer flow could not be forced at a greater magnitude than that of the reference state. Only by increasing the upper and lower layer magnitudes to a large extent (say 50/5) could a determination be made on whether the magnitude of the lower layer flow alone, or the shear between the upper and lower layers has the greater effect on the upper layer flow.

D. COMPARISON WITH PREVIOUS STUDIES

As was previously mentioned, the general circulation in the Monterey Bay is not well documented. Several general trends which appear common in various sources of information do appear to be consistent with the results of the numerical experiments in this study.

Most notably the existence of northward flow along the inshore side of the bay during most of the year (Broenkow and Smethie, 1978) is seen in experiments here independent of the location of the inflow forcing. The model results show that this northward flow is reversed under two circumstances: when the forcing is at the north end of the bay and the lower layer flow is increased with some of this flow in the canyon (Experiment 5), or when no portion of the inflow forcing is over the canyon (Experiment 6). Thus the location of the inflow relative to the canyon and the vertical shear appear important in causing reversals of this generally northward flow.

A presistent anticyclonic flow appears likely over the outer portion of the bay as is evidenced by a thermal high in the 10C and 12C isotherms (Lammers, 1971).

Anticyclonic circulation appears in model experiments here over the outer portion of the bay when lower layer flow velocities are weak and inflow is located at the north end of the bay. When lower layer velocities on the north side of the bay are increased. the anticyclone fills the bay. This anticyclone also exists in Lammers data (Figure 4), even when offshore flow is the Davidson current. None of the experiments here gave anticyclonic flow for forcing from the south. If the poleward flowing Davidson current does enter the bay on the south side, these experiments suggest cyclonic circulation throughout the bay. This is in contrast with the barotropic model results of Garcia (1971), (see Figure 2) which showed anticyclonic or cyclonic motion for poleward forcing offshore. Garcia's model however included viscous lateral shear stresses which are weak in the present model, but could still be important.

IV. DISCUSSION AND CONCLUSIONS

A. ANALYSIS OF RESULTS

A comparison of the upper layer velocity field (Experiment 4) with its associated surface height anomalies demonstrates quite well that the model flow within Monterey Bay is geostrophically balanced.(See Figure 19). As discussed in the previous chapter, the model was particularly sensitive to inflow and outflow boundary conditions, topography and vertical shear. Each of these variables is related to the others. Because of this, the question as to what mechanisms are dominant in forcing the flow within Monterey bay is a complex one. Clearly, each of these variables is important in determining the circulation. But of greater significance is the question of which physical processes are related to each of these variables.

1. Importance of Conservation of Potential Vorticity

If there is no input of vorticity (for example such as might develop due to a wind stress or other frictional effects), potential vorticity in each layer should be conserved following the motion. Because the flow is relatively weak in this study (Rossby number less than 0.05) the quasigeostrophic potential vorticity equations are applicable. For layer thicknesses h_1 and h_2 and for reduced gravity g', these equations are derived in Young, (1987).

$$\partial/\partial t(\nabla^2 p_1 + F_1(p_2 - p_1)) + \beta(\frac{\partial p_1}{\partial x}) = 0 \tag{4.1}$$

$$\partial/\partial t(\nabla^2 p_2 + F_2(p_1 - p_2)) + \beta(\frac{\partial p_2}{\partial x}) = 0 \tag{4.2}$$

$$F_1 = \frac{f_0}{g'H_1} = (\frac{1}{R_{d1}})^2 \tag{4.3}$$

$$F_2 = \frac{f_0}{g'H_2} = (\frac{1}{R_{d2}})^2 \tag{4.4}$$

The effects of the sloping bottom are included in lower layer potential vorticity. For an f-plane such as considered here, the third term due to planetary vorticity is zero in each

31

layer. The remaining terms show that relative vorticity (first term) is generated by vortex stretching at the interface (second term) for the upper and lower layers.

Because of rapid changes of depth in the lower layer associated with the Monterey Canyon, a very large vorticity gradient exists in the lower layer. For lower layer potential vorticity (Equation 4.5)

$$q_2 = \nabla^2 p_2 + F_2(p_1 - p_2) - b \tag{4.5}$$

to be conserved the fluid has to follow contours of the bottom which dominate the quantity q_2, where b is the effect of topography on lower layer potential vorticity $(b = \frac{-f_0}{H_1} d)$, where d = the depth of topography in the lower layer. This is seen by examining potential vorticity in the lower layer for Experiment 4 (U_2= 1 cm/sec) and Experiment 5 (U_2 = 5cm/sec) at day four of these simulations (See Figure 18). The close resemblance of these contours to those of bathymetry confirms that q_2 is dominated by d. Velocity vector plots for these experiments also showed the topographic control of lower layer flow. This argument explains why flows which are initialized over the canyon (North forced reference state) are controlled by the canyon whereas inflow into the bay outside of the canyon (Experiment 6) can follow a path around the canyon.

Whether or not the upper layer responds to topography depends on the relative importance of vortex stretching at the interface $F_1(p_2 - p_1)$. In the weak lower flow case (Experiment 4) the upper layer potential vorticity plot shows that no topographic control is exerted on the upper layer. The upper layer is effectively decoupled from the lower layer and can cross the canyon. However for stronger lower layer flow (Experiment 5) the upper potential vorticity plot shows strong topographic control of the upper layer, and the flow, unable to cross the canyon, has to flow around it.

In Experiment 5 the inflow is barotropic ($U_1 = U_2$).The pressure terms in each layer are given by Equations 4.6 and 4.7;

$$p_1 = g(h_1 + h_2 + d) \tag{4.6}$$

$$p_2 = p_1 - g'h_1 \tag{4.7}$$

For barotropic flow, interfacial distortions are in phase and equal in magnitude to those of the surface. The second term in p_2 is small and $p_1 \approx p_2$. Hence the vortex stretching term in either layer is small. The lower layer equation, rewritten for $p_1 = p_2$ shows that the upper layer must follow the bathymetry as well for barotropic ($U_1 = U_2$) flow.
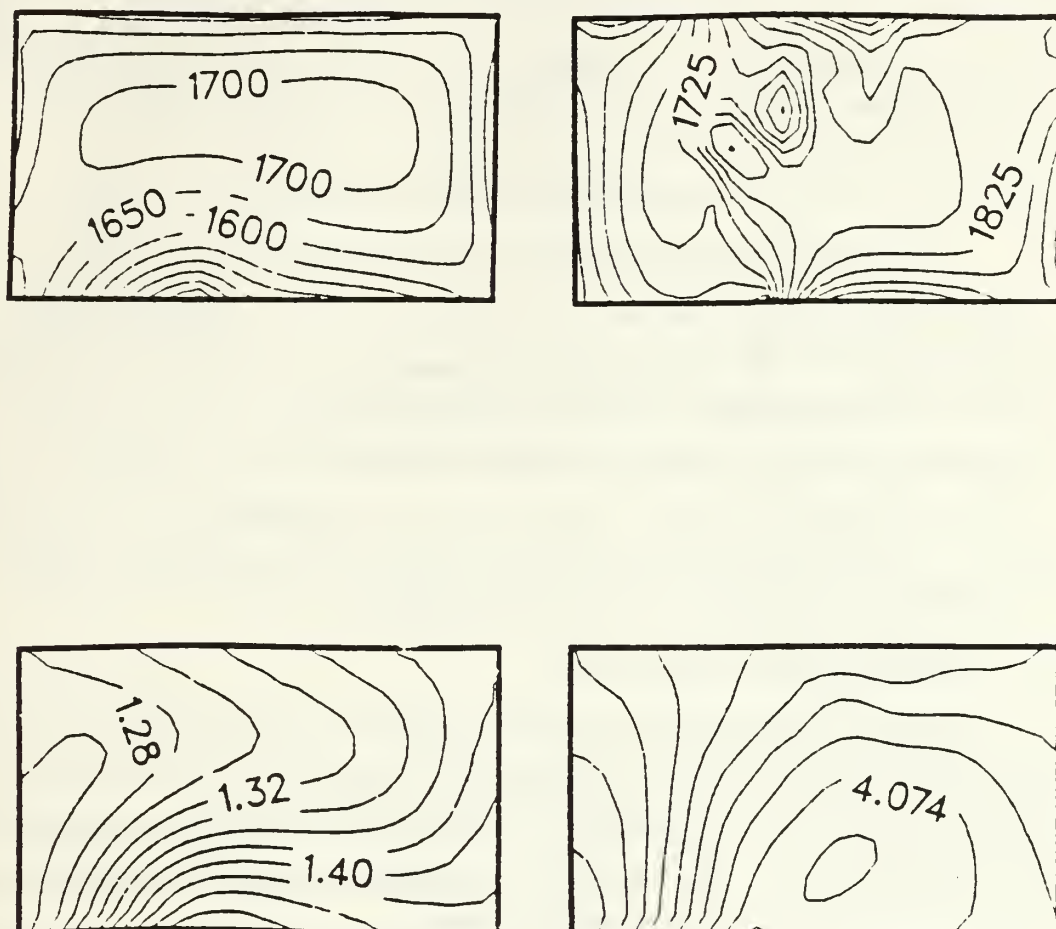
Figure 18. Experiments 4 and 5 pot. vort. and sfc. height anomalies(day4): The upper two figures depict potential vorticity at day four for Experiments 4 and 5, while the lower two figures depict the surface height anomalies for Experiments 4 and 5, also at day four.

2. Importance of the Conservation of Mass Principle

Comparison of the upper layer velocity fields of Experiment 1 and the reference state points out that under certain circumstances (e.g. Experiment 1), the weak cyclonic circulation so evident in the reference state can be produced even without topography. It is very important that this phenomenon be understood. The continuity equation, Equation (4.8) assists in this understanding.

$$(\partial u/\partial x) + (\partial v/\partial y) + (\partial w/\partial z) = 0 \qquad (4.8)$$

In the upper layer velocity field from Experiment 1 the flow is forced in at the northernmost opening of the bay. As the flow follows the boundaries of the bay, it turns first equatorward, and after crossing the center of the bay is forced to turn either eastward or westward. Due to continuity of mass, a portion of the flow turns westwards, towards the bay's exit, while the remainder turns back eastwards, ultimately forming the a cyclonic circulation, similar to that found in the reference state. An examination of model interfacial structure where this flow diverges at the wall indicated that $\partial w/\partial z$ was small and that the flow is horizontally nondivergent.

B. IMPORTANCE OF RESULTS

There have been numerous numerical models run simulating flow over topography. A two layer model however, has not previously been used to study flow over the severe, enclosed topography of Monterey Bay. Due to the extent of the submarine canyon's depth and the relatively rapid circulation which occurs within its boundaries, some very important principles can be studied by examining such a two layered numerical model.

As previously discussed, the behavior of the bay's circulation, particularly when flowing over the deep submarine canyon is dramatically different from a flat bottom / no topography case. These differences can best be explained by considering conservation of vorticity and mass, and the effects of vortex stretching. For relatively slow lower layer flow, the lower layer has little effect on the upper layer flow and surface currents. It is only when the lower layer flow magnitude has increased to a value greater than 5cm/sec that its effect on the upper layer is really felt.

C. RECOMMENDATIONS FOR FUTURE STUDIES

There are several aspects of the model used in this research that could be modified to better simulate flow within Monterey Bay. As mentioned earlier, the effects of wind and tidal forcing, bottom friction and a variable Coriolis force were not considered.

Garcia (1971) determined that the effects of bottom friction and a variable Coriolis force are negligible in comparison with the size, strength of flow, and topography within Monterey Bay. The effects of wind and tidal forcing however, cannot be assumed to be negligible and the inclusion of these forces in the model would certainly enhance its expected accuracy.

A model with at least three layers would give the vertical resolution necessary to properly simulate the flow within Monterey bay as discussed by Breaker and Broenkow (1988) and Bruner (1987). Prior to running a three layered simulation, more observational data must be obtained of the actual flow within Monterey bay.

D. CONCLUSIONS

Model results indicate that the general circulation within Monterey Bay is consistent with geostrophic, vorticity-conserving flow over bottom topography. The model is sensitive to the position of the inflow and outflow boundaries in relation to topography and to the vertical inflow shear.

Closed circulations within the bay's upper layer are not only possible, but indeed are highly probable. The strength of these closed circulations are highly dependent on the strength of the lower layer flow. Any attempt to model circulation over topography must include these effects.

The results of the study are consistent with several aspects of the observed Monterey Bay circulation. The predominantly northward flow inside the bay can occur independently of north or south location of inflow into the bay relative to the canyon. The results also indicate that anticyclonic circulation can exist over the outer portion of the bay for northern location of inflow when lower layer inflow is weak.

APPENDIX

A_h Lateral friction coefficient

$D(x,y)$ Variable depth of topography

H_1 Upper layer thickness

f   Coriolis parameter for latitude

g   Gravitational acceleration

g ′   Reduced gravitational acceleration $= g(\rho_2 - \rho_1)/\rho_1$

h_i Instantaneous layer thickness

H_i Upper (i = 1) and lower (i = 2) layer mean thickness

L   Horizontal scale length

p_1 pressure in the upper layer $= g(h_1 + h_2 + d)$

p_2 Pressure in the lower layer $= p_1 - g'h_1$

R_d First internal Rossby radius of deformation $= g'H_1H_2/f^2(H_1 + H_2)^{1/2}$

R_0 Rossby number $= U/fL$

U   Scale velocity

u_i, v_i Velocities in the x and y directions

U_i, V_i Transport in the x and y directions

x,y   Cartesian coordinates directed N and W respectively

γ basin rotation angle from east

$\Delta x, \Delta y$ Grid spatial resolution

Δt Model time increment

∇ Gradient operator $= \partial/\partial x + \partial/\partial y$

∇^2 Laplacian operator $= \partial^2/\partial x^2 + \partial^2/\partial y^2$

b   Effect of topography on lower layer vorticity

d   Lower layer thickness

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